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SOUND [illegible] ENGINE COMPANY

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MEASUREMENTS OF THE ATTENUATION OF A REPEATED SHOCK WAVE

By

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Technical Report No. 3

on the

High Amplitude Sound Abatement Research Program

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INTRODUCTION

In Technical Report No. 45, a siren and microphone system capable of respectively producing and measuring sound waves of large amplitude is described.

This report covers measurements, using this equipment, of the rate of attenuation of such large amplitude waves in the frequency range 30-200 c.p.s. and discusses the results in terms of known theories of attenuation.

MEASUREMENTS

Measurements of amplitude and wave form were made as a function of distance along a 10" diameter 60 foot long tube connected to the siren. In all cases of interest the wave more or less closely approximated a sawtooth wave form. Fig. 1 shows a group of measured wave forms at 80 c.p.s. at various points along the tube. The number at the top of each frame indicates the distance in feet from the siren. These oscillograms were made during the recording of Fig. 3. The output of the microphone was fed into a Hewlett Packard 400C voltmeter. The meter responds to the average rectified voltage but the scale is calibrated in terms of the r.m.s. voltage of a sine wave. Under these circumstances it can be shown that when a sawtooth wave is fed into the meter an addition of 11 db to the observed reading will give the voltage change across the discontinuity in the

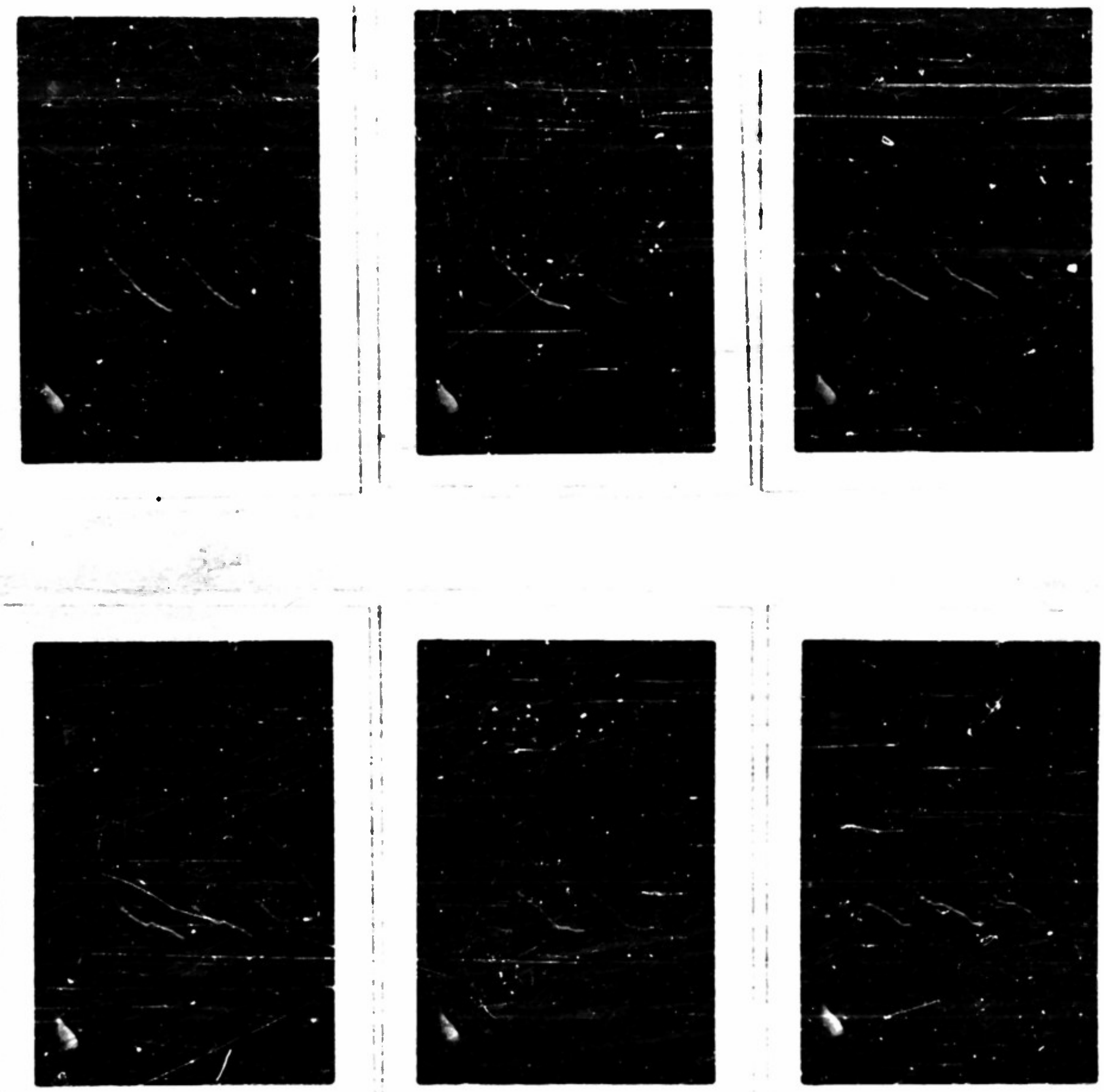

Figure 1. Oscillograms of the sound pressure at various points along the tube. 80 c.p.s., plenum pressure 22.4 inches Hg. The numbers at the top of each frame indicate the distance in feet from the siren to the microphone. These were made during the recording of Figure 3.

wave. This figure of 11 db was obtained by calculation and checked directly. The resultant sensitivity of the microphone was such that the meter read 1 volt when the pressure discontinuity was .136 atmospheres for a sawtooth wave. Of interest in discussing the results is the quantity $\delta = \frac{P_2 - P_1}{P_1}$ (see Fig. 5). Assuming P_o is equal to $\frac{P_1 + P_2}{2}$ it is seen that

$$\frac{1}{\delta} = \frac{1}{\frac{P_2 - P_1}{P_o}} - \frac{1}{2} \qquad (1)$$

The voltage was fed to a recorder which had been previously calibrated. Figures 2 - 4 show observed values of the average pressure swing as a function of distance along the tube for three different frequencies. For frequencies below 100 c.p.s. the standing wave resulting from reflection at the termination became progressively greater. In all such cases a monotonically decreasing average curve (see Fig. 2) was obtained by averaging consecutive minima and maxima. Values of $\frac{P_2 - P_1}{P_o}$, and from Eq. (1), $1/\delta$, versus distance were obtained from these curves.

SOURCES OF ATTENUATION

(1) Attenuation Due to Tube Walls

It is known that for small amplitude waves the attenuation at the walls of the tube will be the principle agent for acoustic attenuation. For a simple sine wave of frequency, f, in air at a sound velocity, c, propagated in a tube of radius R ($R \ll \lambda$, the wavelength),

$$\frac{d\delta}{\delta} = a_1 \, dx , \qquad (2)$$

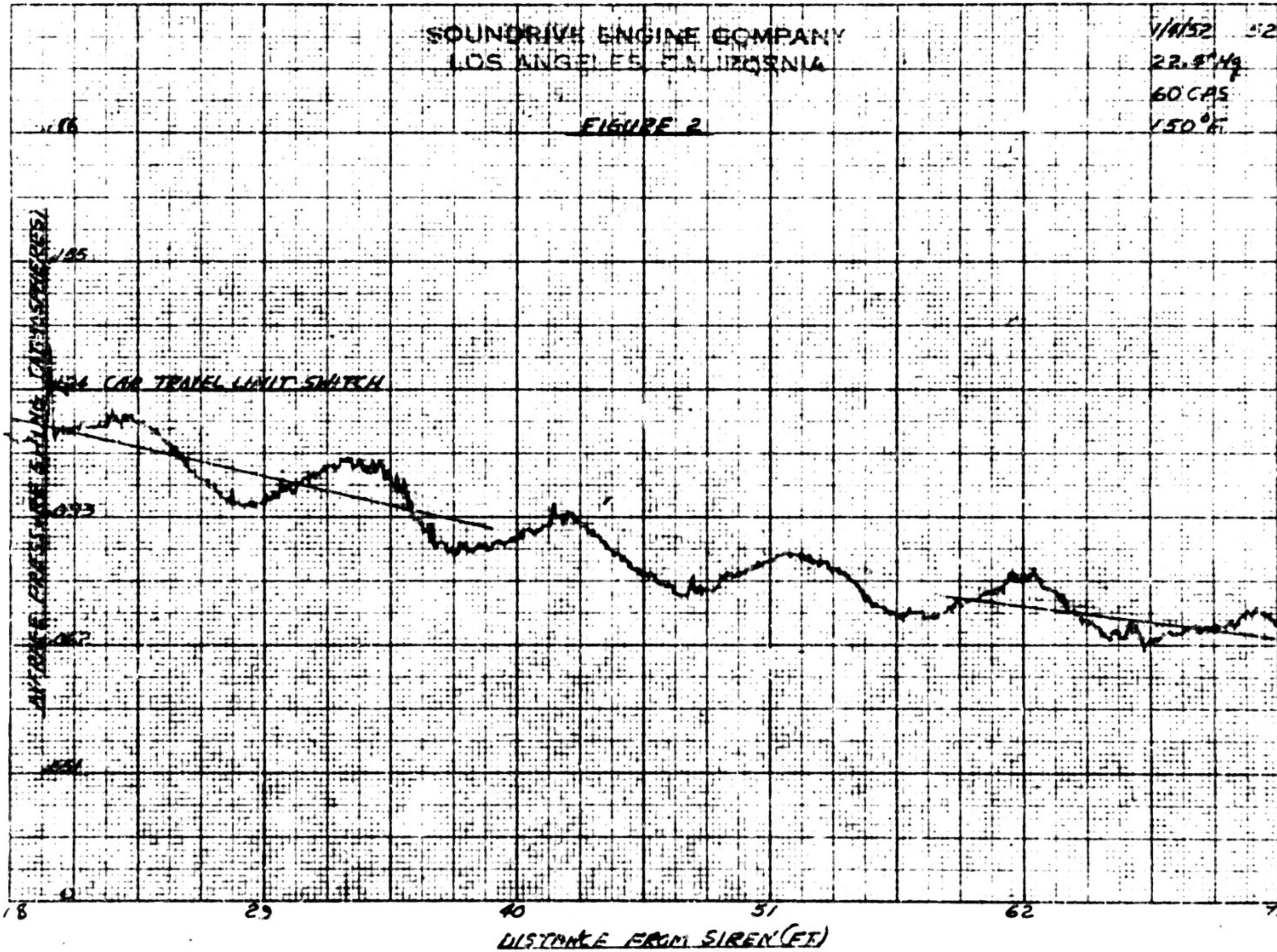
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FIGURE 2
1/4/52 52
22.5" Hg
60 CPS
150°F
CAR TRAVEL LIMIT SWITCH
.16
.155
.093
.062
0
18
29
40
51
62
73
DISTANCE FROM SIREN (FT)

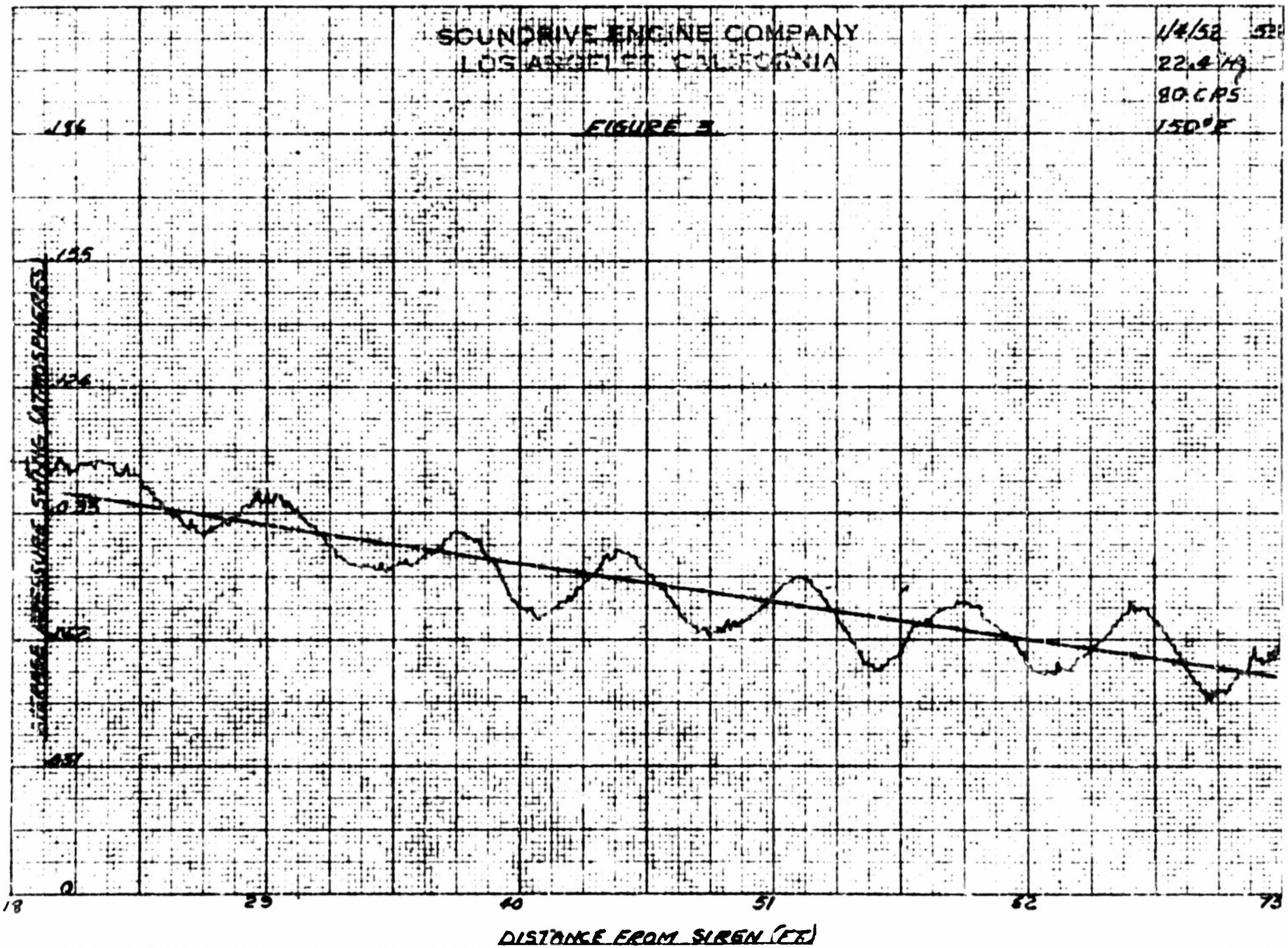
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FIGURE 3
1/4/52
22.4 Hg
80 CPS
150°F
.156
.155
.154
.153
.152
.151
0
AVERAGE PRESSURE SWING (ATMOSPHERES)
18
29
40
51
62
73
DISTANCE FROM SIREN (FT.)

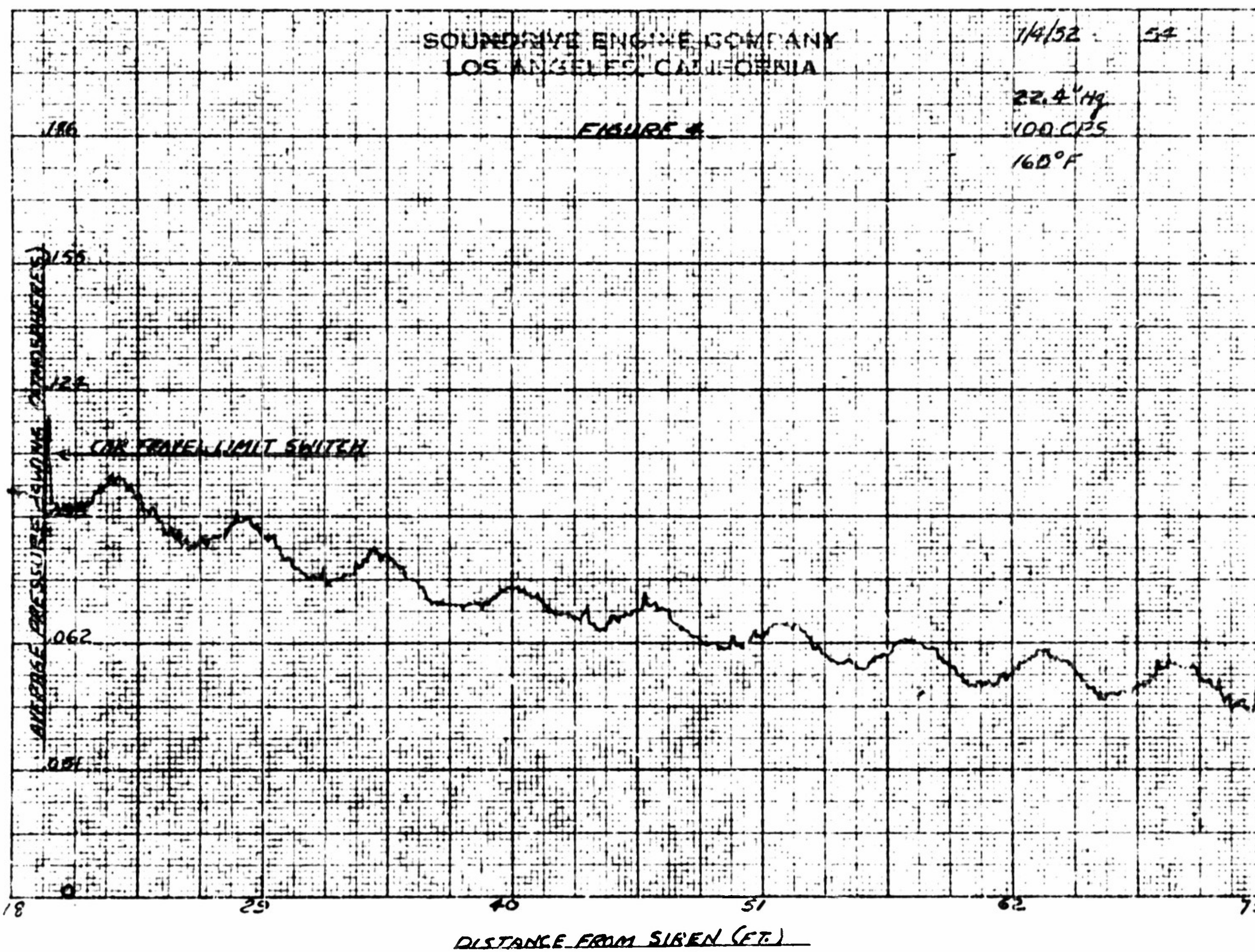
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FIGURE 4
7/4/52
54
22.4" Hg
100 CPS
160°F
AVERAGE PRESSURE SWING (ATMOSPHERES)
.186
.156
.124
.062
.031
0
CAR TRAVEL LIMIT SWITCH
18
29
40
51
62
73
DISTANCE FROM SIREN (FT.)

where

$$a_1 = \frac{1}{RC}\sqrt{\pi f \nu'}\,, \tag{3}$$

and where ν' depends on the kinematic coefficient of viscosity and the thermometric conductivity coefficient for air. Using R = .417 ft., $c = 3.54 \times 10^4$ cm/sec, $\nu' = 0.355$ cm^2/sec,

$$a = 0.68 \times 10^{-4}\sqrt{f} \quad \text{per foot}\,. \tag{4}$$

From (5) it is seen that a small amplitude 100 cycle sine wave would have its amplitude reduced by about 4% in travelling 60 ft. down the 10" diameter tube - a much smaller decrease than that observed in the present study.

Now actually the waves studied were sawtooth in character. It is assumed that this sawtooth wave is attenuated by viscosity and heat conductivity at the walls just as an infinitesimal amplitude wave would be, that all components of the wave decay according to Eq. (4), where f is the frequency of the particular component in question, and that the rate of loss of energy is equal to the sum of the rates of loss of energy of all the components. That is, if E_n is the energy associated with the nth harmonic of the sawtooth, and if f_1 is the frequency of the fundamental, then

$$\frac{dE_n}{E_n} = 2\,\frac{d\delta}{\delta} = 1.36 \cdot 10^{-4}\sqrt{n f_0}\,.$$

Now,

$$E_n = \frac{E_1}{n^2}$$

$$\therefore \; dE_n = 1.36 \cdot 10^{-4} \sqrt{f_1}\, E_1 n^{-3/2}$$

and

$$\frac{dE}{dx} = \sum_{n=1}^{\infty} \frac{dE_n}{dx} = 1.36 \cdot 10^{-4} \sqrt{f_1}\, E_1 \sum_{n=1}^{\infty} n^{-3/2},$$

and

$$\frac{1}{\delta}\frac{d\delta}{dx} = \frac{1}{2E}\frac{dE}{dx} = 0.68 \cdot 10^{-4} \sqrt{f_1}\, \frac{\sum n^{-3/2}}{\sum n^{-2}}.$$

where

$$\left.\begin{aligned} \frac{d\delta}{\delta} &= \alpha_2\, dx, \\ \alpha_2 &= 1.07 \cdot 10^{-4} \sqrt{f_1} \text{ per foot} \end{aligned}\right\} \text{------} \qquad (5)$$

It is well understood that the assumptions leading to Eq. (5) are too simple for the large amplitude waves which are being studied here. Eq. (5) must be regarded as a zero order correction for the effect of the tube walls. A first order correction for this effect is, however, not available and must await further experimentation and, or, theoretical analysis.

(2) Attenuation Due to Shock Character of Wave

A first order theory for the rate at which high amplitude plane progressive sound waves are attenuated was developed in Technical Report No. 42. In this report it was pointed out that the limiting form for a high amplitude plane sound wave was a sawtooth (see Fig. 5)

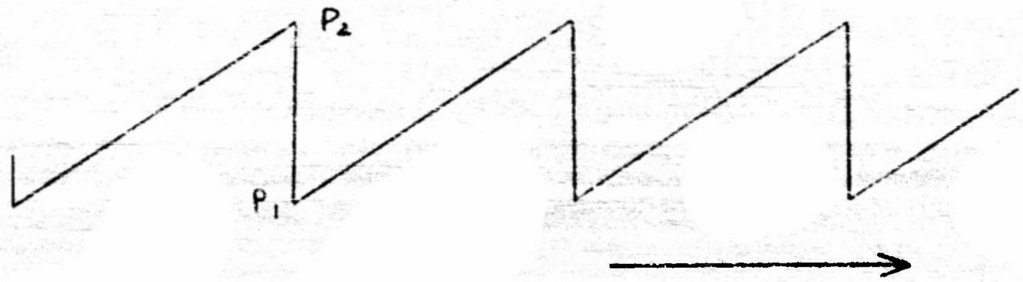

Fig. 5

where $P_2 - P_1$ is the pressure discontinuity and $\delta = \frac{P_2 - P_1}{P_1}$ is an order of magnitude less than 1. The attenuation rate for the plane wave could be expressed by the law

$$\frac{d}{dx}\left(\frac{1}{\delta}\right) = \frac{\gamma+1}{2\gamma} \cdot \frac{1}{\lambda} \tag{6}$$

where γ is the ratio of the specific heat at constant pressure to that at constant volume. Since the velocity of the wave will be equal to the velocity of sound, c, at the average temperature in the wave, the wave-length is just equal to the ratio of this velocity to the frequency.

(3) Summation of Attenuative Effects of Walls and Shock Character of Wave

If it is assumed that the effects represented by Eq. (5) and (6) are additive, then

$$-\frac{d\delta}{dx} = a_2\delta + a_3\delta^2, \tag{7}$$

where $a_3 = \frac{\gamma+1}{2\gamma\lambda}$,

and
$$\frac{1}{\delta} - \frac{1}{\delta_0} = \frac{a_3}{a_2}\left(e^{a_2 x} - 1\right) + \frac{1}{\delta_0}\left(e^{a_2 x} - 1\right),$$

where $\delta_0 = \delta$ at $x = 0$. Since $a_2 x$ is very small in this experiment,

$$\frac{1}{\delta} - \frac{1}{\delta_0} = a_3 x + \left(\frac{a_3 x}{2!} + \frac{1}{\delta_0}\right) a_2 x. \tag{8}$$

and since the first term on the right hand side of (8) predominates,

$$\frac{1}{\delta} - \frac{1}{\delta_0} = a_3 x + \left(\frac{1}{\delta}\right)_{AV.} a_2 x, \tag{8a}$$

where
$$\left(\frac{1}{\delta}\right)_{AV.} = \frac{1}{2}\left(\frac{1}{\delta} + \frac{1}{\delta_0}\right).$$

D.C. FLOW OF AIR THROUGH THE TUBE

In the present series of measurements no attempt was made to bypass the d.c. airflow associated with the operation of the siren. Nor is the velocity of the air flow in the tube well known. Preliminary attempts to measure the velocity using a pitot tube were highly unsuccessful since the pitot tube responded not only to the dynamic pressure due to d.c. flow but also to radiation pressure effects of the sound. Moreover, this latter effect was variable, depending on the instantaneous configuration and length of the air column between the opening of the tube and the mercury manometer, the radiation pressure being dependent on the acoustic tuning of this air column. Thus, with a given compressor speed, if the siren chopping rate was changed, the mercury could be observed to suddenly shoot out of the U-tube, presumably when the air column approached resonance. This effect is mentioned as an example of the complications which sometimes occur in measurements in intense sound fields. It is felt that this difficulty can be obviated if a long narrow gauge tube is used between the pitot element and the manometer; the diameter and length being prescribed by the requirement that the sound wave be sufficiently attenuated before reaching the manometer.

In the present instance reliance for velocity data was based on the published rated performance of the compressors, given in Table I.

Table I

Pressure at Siren Inches Hg	Vel. in 10" tube meters/sec
22.4	87
18	78
12.2	64
6	46
3	38
1.5	26

It was assumed that the only effect of this convective flow was to alter the effective distance of sound propagation in the tube, changing it by the factor, $\frac{c}{c+v}$, where v is the convective velocity.

DISCUSSION OF MEASURED RESULTS

Of principle interest is the attenuation due to the shock character of the wave. For this reason the second term on the right of Eq. (8a) is subtracted from the measured values of $1/\delta$ and these "corrected values" of $1/\delta$ are plotted against x (appropriately corrected for convective velocity effects as just described). The results of a series of measurements are shown in Figs. 6-10. At each frequency measurements were made at a number of siren chamber pressures which accounts for the multiplicity of data shown. The numbers associated with each line are the ratio of the slope of the line to that given by Eq. (6). It is fully recognized that Eq. (6) properly holds only for large values of $1/\delta$ (say greater than 10) whereas the measured values extend to low values of $1/\delta$, and that, consequently, Eq. (6) can only approximate the situation for the low values of $1/\delta$.

It is seen that except for the lowest amplitude 100 c.p.s. curve it is approximately true that the slope of the $1/\delta$ versus x curve lies between 50% and 100% of the value given by $\frac{\gamma+1}{2\gamma}\cdot\frac{1}{\lambda}$. Most of the observed values are close to 70% of this value.

Secondly, it is seen that while the evidence is very far from conclusive, an extrapolation of the data to lower amplitudes certainly casts doubt on the possibility that for values of δ less than, or equal to, 0.1, the slope will become as great as $\frac{\gamma+1}{2\gamma}\cdot\frac{1}{\lambda}$.

It would be of considerable interest to (1) extend the analysis of the decay of repeated shock waves to higher amplitudes (say $\delta = 1$) and (2) extend measurements to the smaller amplitude region, $\delta < 0.1$.

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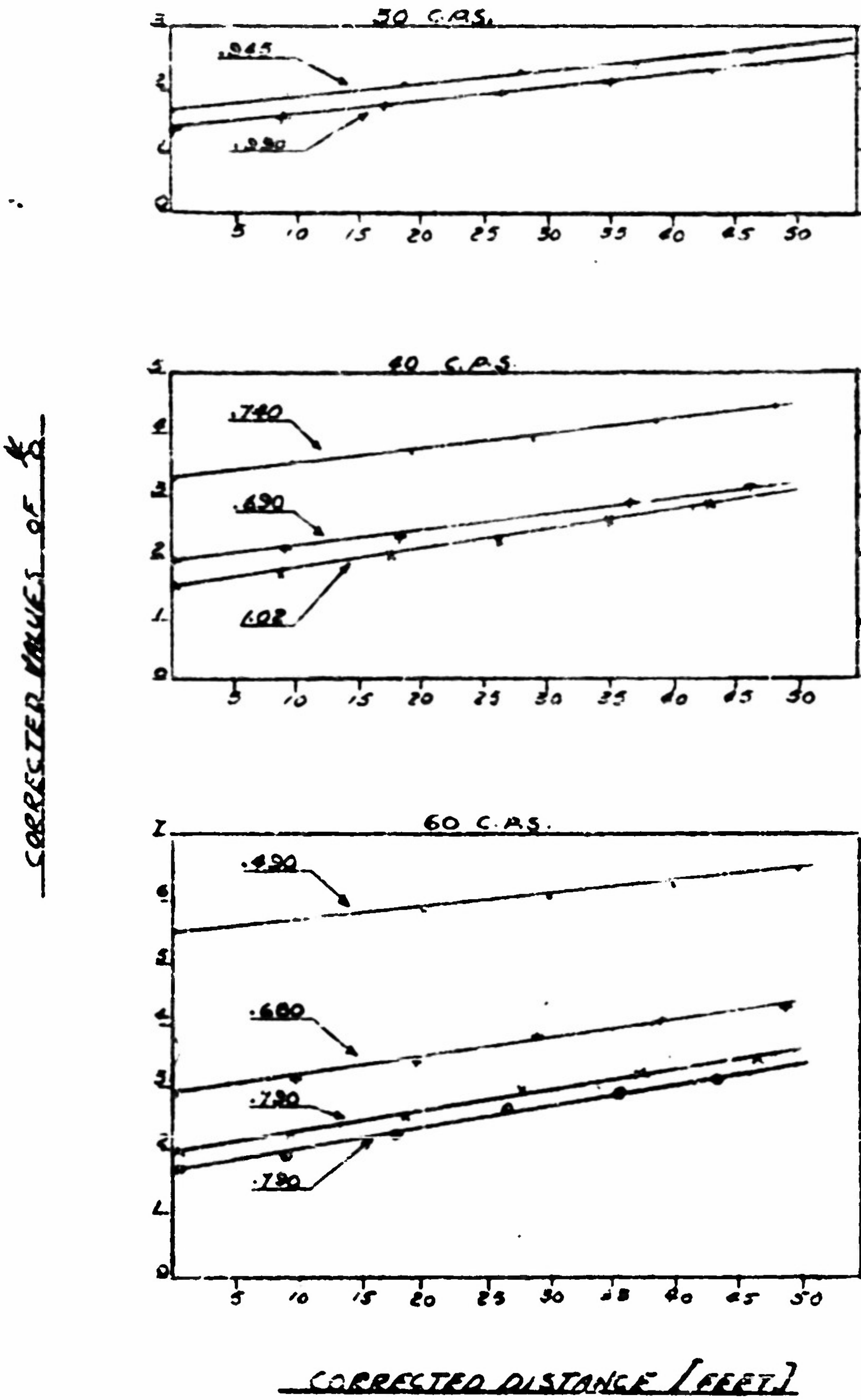
FIGURE 6



NOTE:
Numbers associated with each line are the ratios of the slopes of the lines to those given by Eq. (6)

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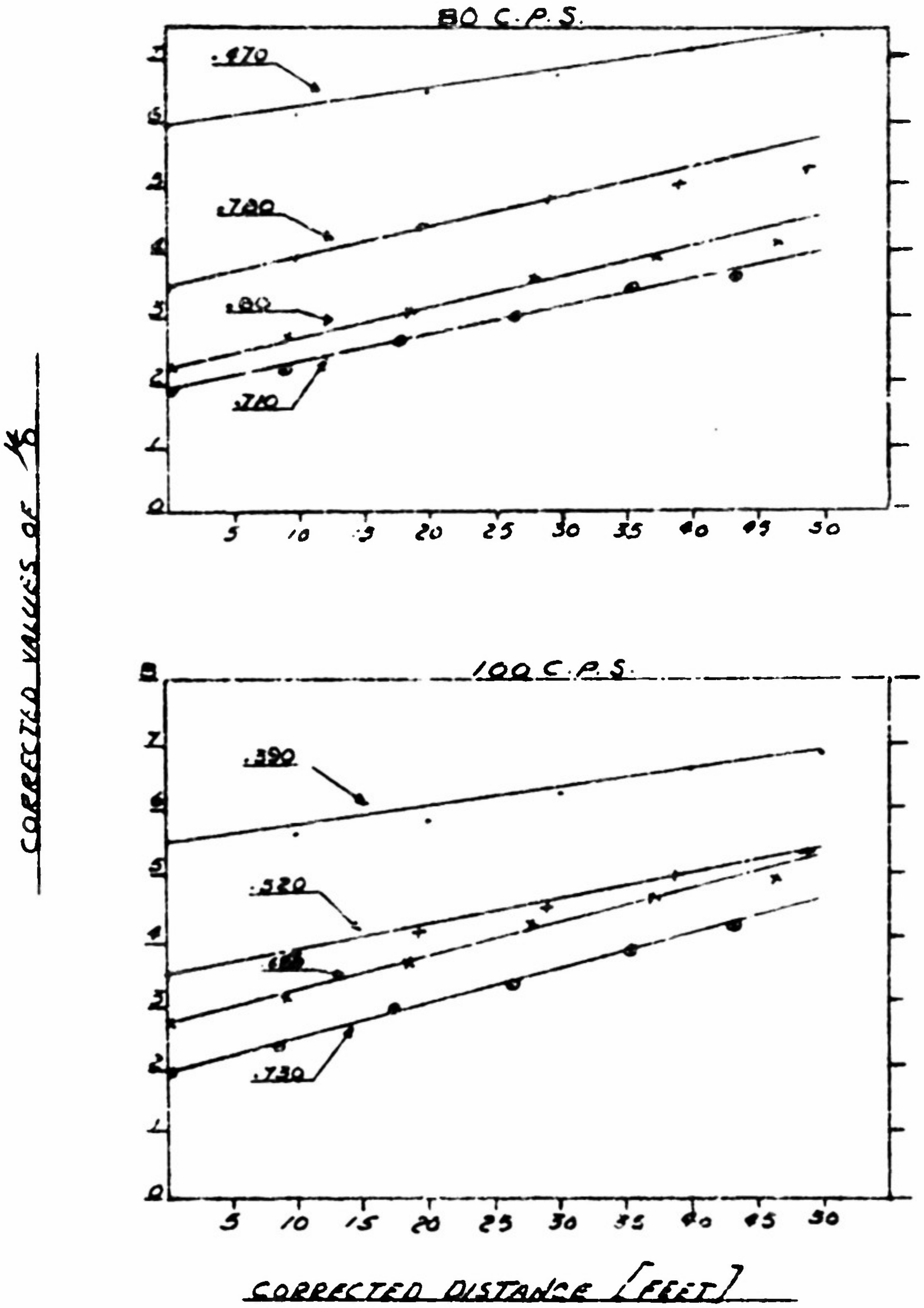
FIGURE 7



NOTE: Numbers associated with each line are the ratios of the slopes of the lines to those given by Eq. (6)

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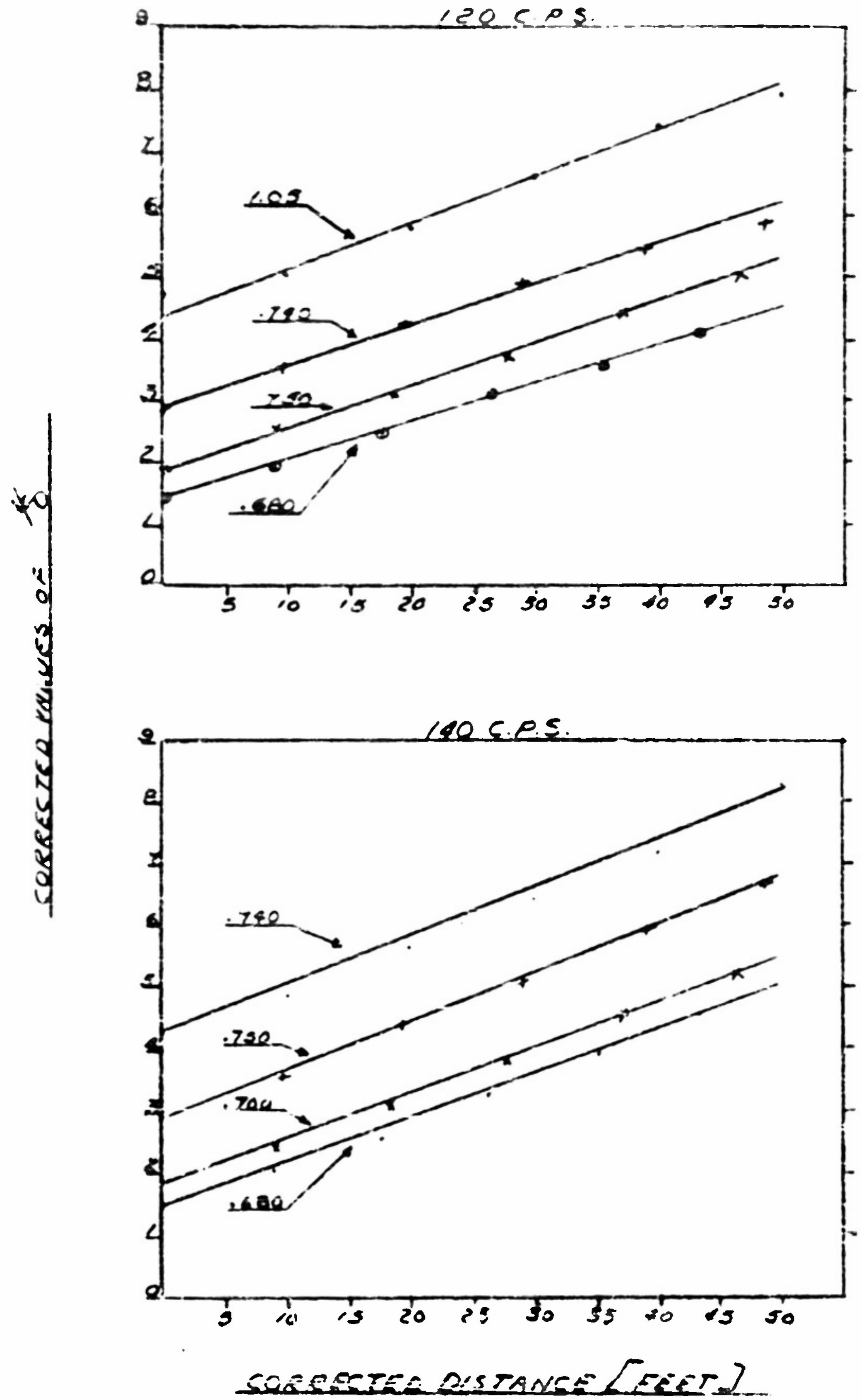
FIGURE B



NOTE: Numbers associated with each line are the ratios of the slopes of the lines to those given by Eq. (6)

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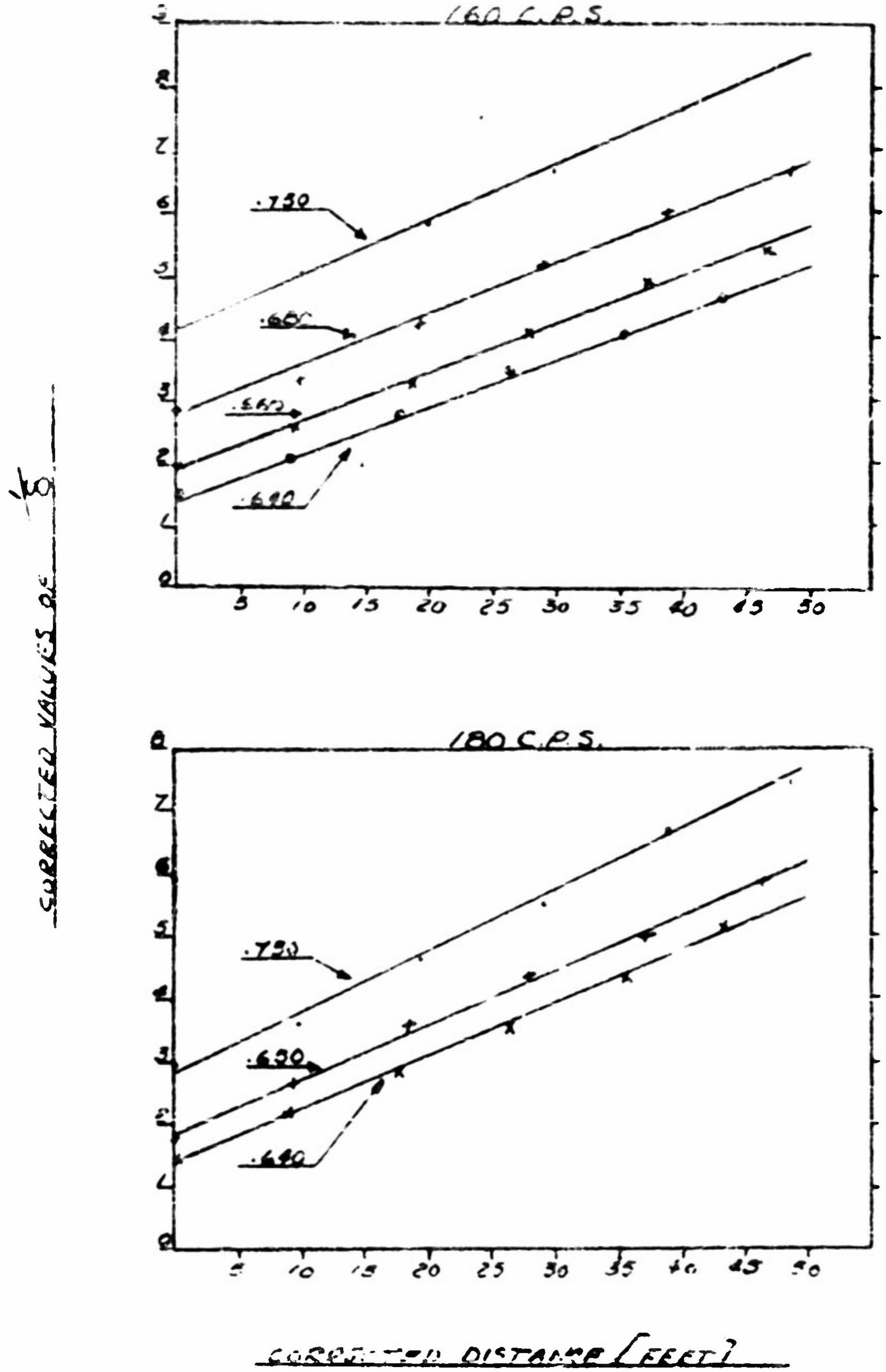
FIGURE 9



NOTE: Numbers associated with each line are the ratios of the slopes of the lines to those given by Eq. (6)

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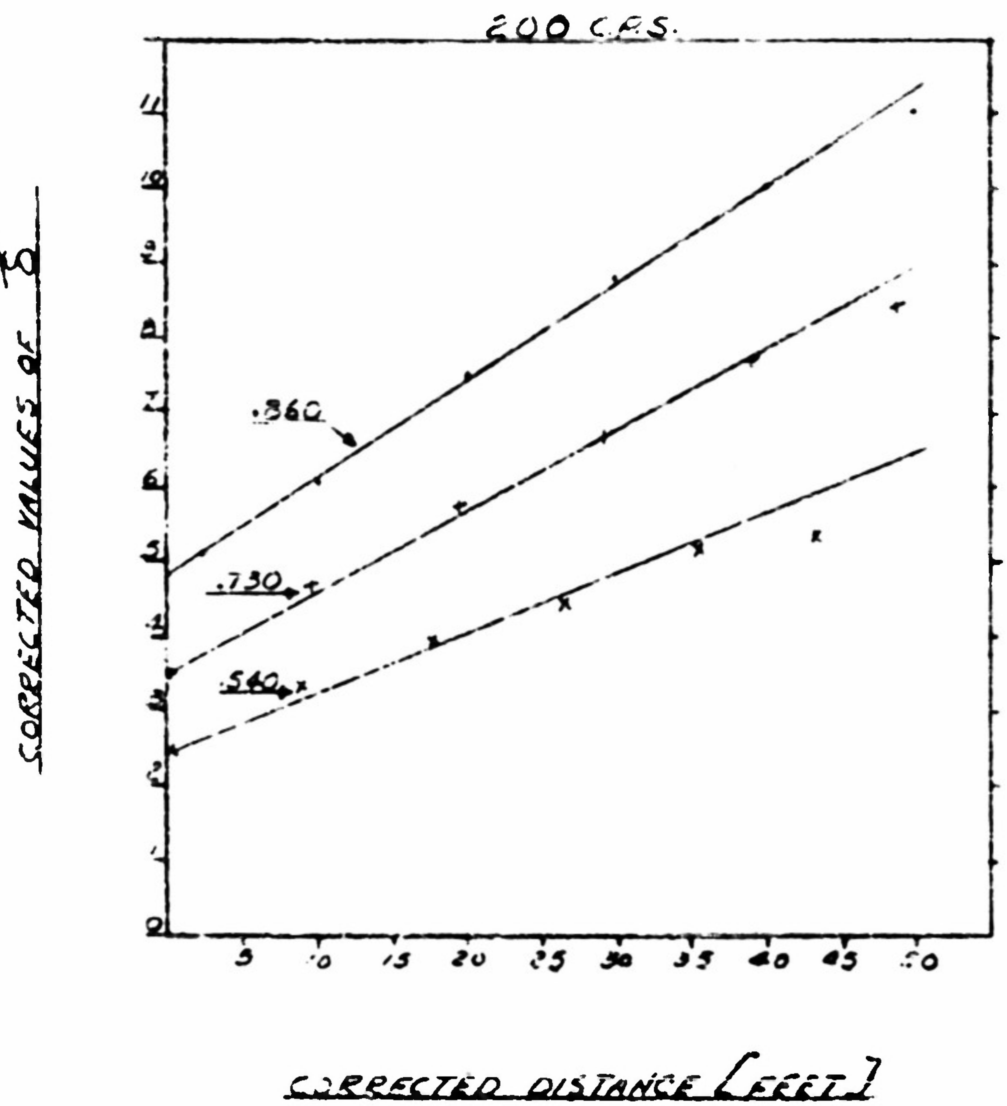
FIGURE 10



NOTE:
Numbers associated with each line are the ratios of the slopes of the lines to those given by Eq. (6)

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